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Effectiveness of interventions to reduce household air pollution from solid biomass fuels and improve maternal and child health outcomes in low- and middle-income countries

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Effectiveness of interventions to reduce household air pollution from solid biomass fuels and improve maternal and child health outcomes in low and middle-income countries; a systematic review and meta-analysis

Running Title: Health and solid biomass fuel interventions

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Abstract

Interventions to reduce Household Air Pollution (HAP) are key to reducing associated morbidity and mortality in low- and middle- income countries (LMICs); especially among pregnant women and young children. This systematic review aims to determine the effectiveness of interventions aimed to reduce HAP exposure associated with domestic solid biomass fuel combustion, compared to usual cooking practices, for improving health outcomes in pregnant women and children under five in LMIC settings.

A systematic review and meta-analysis was undertaken with searches undertaken in MEDLINE, EMBASE, CENTRAL, GIM, ClinicalTrials.gov and Greenfile in August 2020. Inclusion criteria were experimental, non-experimental or quasi-experimental studies investigating the impact of interventions to reduce HAP exposure and improve associated health outcomes among pregnant women or children under five years. Study selection, data extraction, and quality assessment using the Effective Public Health Practice Project tool, were undertaken independently by two reviewers.

17 out of 7293 retrieved articles (seven pregnancy, nine child health outcome; 13 studies) met the inclusion criteria. These assessed improved cookstoves (ICS) (n=10 studies), ethanol stoves (n=1 study) and Liquefied Petroleum Gas (LPG) (n=2 studies) stoves interventions. Meta-analysis showed no significant effect of ICS interventions compared to traditional cooking for risk of preterm birth (n=2 studies), small for gestational age (n=2 studies) and incidence of acute respiratory infections (n=6 studies). Although, an observed increase in mean birthweight was observed, this was not statistically significant (n=4). However, ICS interventions reduced the incidence of childhood burns (n=3; observations = 41,723; Rate Ratio:0.66 [95% CI: 0.45-0.96]; I^2:46.7%) and risk of low birth weight (LBW) (n=4; observations = 3456; Odds Ratio:0.73 [95% CI: 0.61-0.87]; I^2: 21.1%).

Although few studies reported health outcomes, the data indicate that ICS interventions were associated with reduced risk of childhood burns and LBW. The data highlight the need for the development and implementation of robust, well-reported and monitored, community-driven intervention trials with longer-term participant follow-up.

Key words: Environmental health; intervention effectiveness; indoor air pollution, pregnancy outcomes, child health outcomes; health improvement.

Systematic review registration: Protocol identifier: https://doi.org/10.1186/s13643-021-01590-z. PROSPERO ID: CRD42020164998.

Practical implications:

- A number of health benefits are identified by using an improved cookstove (ICS) including reduced risk of low-birth weight, burns, and acute lower respiratory infections within high altitude settings.
- Considering uptake and compliance of the intervention, alongside the health benefits, provides contextual relevance for interpretation of findings of both the included studies and this systematic review.
- Future intervention studies should actively consider in their study design i) Improving standardisation of outcome definitions, timing of intervention deployment and duration of follow-up to outcome assessment, ii.) Taking more detailed measurements and clear reporting of intervention compliance, iii.) Providing an assessment of the potential of short-medium term interventions.
- Adopting and taking into consideration these recommendations would inform research priorities and enable robust policy formation for delivery of HAP interventions.

1. Introduction

Complex interventions such as those to reduce household air pollution (HAP) which include several multiple interacting components, are challenging to evaluate due to practical and methodological difficulties. However, evaluation is necessary to assess important health consequences and improve population health.[1] HAP is produced from the burning of biomass (wood, dung charcoal and crop residue), coal and kerosene for cooking, heating and lighting in typically poorly ventilated settings, generating hazardous levels of carbon monoxide (CO), particulate matter (PM), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2).[2]

Interventions to reduce HAP exposure include introduction of cleaner fuels (e.g., Liquefied Petroleum Gas (LPG), ethanol, electricity, solar stoves, biogas, natural gas)[3] which could reduce levels to below the World Health Organization's Indoor Air Quality (WHO-IAQ) guidelines if fully adopted. At a clean energy transition stage fuel 'stacking', or incomplete uptake may occur, whereby users continue to use traditional cooking methods and fuels alongside cleaner sources; thereby reducing efficacy of the intervention.[4] Populations in low and middle-income countries (LMICs) often face multiple barriers to adoption of HAP interventions, including accessibility, affordability, lack of sustainable infrastructure and interventions not meeting cultural and social preferences. This is particularly the case with long-term interventions that require significant transition and behavioural adaptation. WHO Indoor Air Quality Guidelines (2014) focus particular attention upon reducing pollutants as much as possible – by clean fuel transition - given the need to reduce PM2.5 exposure to low levels to generate health benefits[5]; recommendations which have been reiterated in the updated global air quality guidelines (2021).[6] However, the guidelines also provide evidence-based recommendations for policies to be enacted within the clean fuel transition period (including introduction of Improved Cookstoves), recognising that intermediate steps will be necessary in many low-income settings. These include measures such as improved cookstoves (ICS);[7] improved biomass fuels (e.g., briquettes, biomass pellets)[8] and behavioural changes (e.g., ventilation, outdoor cooking)[7] to address the global burden of arising disease from HAP.[9] However, these often fail to achieve substantive reduction in HAP levels sufficient to prevent health harms and improvements may not meet WHO-IAQ Interim Targets.[7]

Interventions are needed to reduce the health, socio-economic and environmental consequences associated with HAP, which disproportionately affect pregnant women and young children.[10] In pregnancy, causally associated health outcomes with HAPs[11] include gestational hypertension, intrauterine growth retardation (IUGR) preterm birth, stillbirth, birthweight, and perinatal mortality.[12] In children aged under five years investigated health outcomes include acute lower respiratory infection (ALRI), asthma, otitis media, impaired neurodevelopment and mortality in early life.[13,14]

Previous systematic reviews have focused on the effect of interventions upon HAP concentrations or exposure levels[15] or have selected specific interventions (e.g., ICS)[7,16] or health outcomes,[17,18] without assessing the benefit of intervention options upon maternal and child health. Systematic reviews on uptake and sustained use of both ICS and adoption of cleaner fuels[19] have been undertaken, highlighting contextual and compositional factors that should be considered when planning and implementing such interventions. This systematic review aims to provide an evidence synthesis for the overall benefit of HAP interventions, compared to usual practice from experimental and non-experimental studies, on maternal and child health outcomes in pregnant women and children under five in LMIC settings. Sustained uptake of these HAP interventions is also discussed.

2. Methods

A detailed protocol for the systematic review and meta-analysis has been published previously[20] and registered on PROSPERO (ID: CRD42020164998).[21] The focus of this review is any domestic intervention aiming to reduce HAP exposure associated with cooking, heating and lighting and the associated effect upon pregnancy and under five child health outcomes, among those living in LMICs.

2.1. Search strategy and selection

In August 2020 MEDLINE (in process and 1947 – present); EMBASE (1947 – present); CENTRAL; The Global Index Medicus (GIM) (WHO, 2020a); ClinicalTrials.gov and GreenFILE [23] were searched using index and free text terms for "Population" AND ("Intervention" OR ("Household Air Pollution" AND "LMICs") (MEDLINE search strategy in Appendix 1). Reference lists of included studies, and relevant systematic reviews identified by searching Epistemonikos,[24] were viewed to capture any additional studies. The WHO International Clinical Trials Registry Platform (ICTRP)[25] was searched later in September 2020 due to earlier closure of the portal for Covid-19 research only. Article screening (by title and abstract) and full paper selection were undertaken independently by two reviewers (HL, JS, KEW or EDC), with differences in article selection discussed and resolved as a group.

2.2. Eligibility criteria

Study eligibility was determined using Population-Intervention-Comparator-Outcome-Study design (PICOS) criteria (Table 1). The study population was defined as pregnant women and/or children under five years, residing in LMICs, as defined by the OECD Development Assistance Committee (DAC) list[26] at the time the studies were completed, who are exposed to HAP produced from cooking, heating and lighting with solid biomass fuels. Interventions (i.e., cleaner fuels, structural (e.g., improved cookstoves, chimneys), behavioural) had to target solid biomass cooking, heating or lighting to reduce HAP, which was compared to control groups (i.e., usual practices) or an alternative intervention (i.e., any other intervention within the inclusion criteria).

Studies had to report at least one health outcome related to the pregnancy/perinatal period (within one week of birth) (e.g., IUGR, birthweight, low birth weight, preterm birth, pre-eclampsia, blood pressure, gestational diabetes, maternal mortality, perinatal/infant mortality, stillbirth and miscarriage) or in children under five years (e.g., upper and lower respiratory tract infections, pneumonia, asthma, respiratory distress syndrome, otitis media, impaired neurodevelopment, mortality and burns), previously associated with HAP. Eligible study designs were randomised control trials (RCTs), non-randomised control trials and quasi-experimental or natural experimental studies (including before-after studies and interrupted time-series studies, if pre-and post-intervention health outcomes were recorded).

There was no exclusion by publication date, language or type of publication, with exclusion only occurring when all five areas of the PICOS inclusion criteria were not met.

2.3. Data extraction

Data extraction of included studies was undertaken independently by two reviewers (HL, JS or KEW) and any disagreements were discussed and if necessary adjudicated (by EDC). Data extraction used an adapted (to study design) Cochrane Public Health Group data extraction form, collecting information on study characteristics (i.e., population, geographical setting, inclusion and exclusion criteria), health outcomes (i.e., type of outcome, definitions, scales and time points measured) and interventions details (i.e., type of intervention and comparators, uptake and adoption, air pollution measurement details). Authors were contacted if further clarification or information was required.

2.4. Risk of Bias

Quality and risk of bias was assessed using the Effective Public Health Practice Project;[27] independently by two reviewers (HL, JS or KEW), adjudicated by EDC; at a study level based on the primary outcome. The quality and bias assessment was reported for six components (selection bias, study design, confounders, blinding, data collection methods, withdrawals and dropouts). It was accepted that blinding and random allocation of participants may not have been fully possible, given the nature of the interventions and settings.

2.5. Evidence synthesis

Narrative synthesis was undertaken for each unique population-intervention-outcome triad and for intervention compliance, defined as the uptake and sustained use of the intervention. Meta-analyses, were undertaken in STATA Version 16.1[28]. A random effects model was applied due to the environmental and methodological variation between studies contributing to each analysis; for example differences between specific types of cook stove (intervention) or biomass composition (comparator). The Sidik and Jonkman method was used due to the low number of studies included in each meta-analysis as it reflects uncertainty in the estimation of between-study heterogeneity through widening the confidence interval.[29–31] For comparisons, continuous data were reported as mean differences and standard deviations, dichotomous data as odds ratios (95% confidence interval (CI)) and rate ratios (95% CI). In each meta-analysis, variability in effect estimates between studies beyond that expected by chance alone was quantified with the I^2 statistic. The Chi^2 test for heterogeneity and the between study-variance (Tau^2) were also computed. Where I^2 indicated substantial heterogeneity [29] further sub-analysis was undertaken by geographic region (e.g., Africa, Asia etc.) as defined by the United Nations.[32] Additionally, an exploratory analysis was undertaken for birthweight and LBW, due to the discovery of a variation in timing of deployment of the intervention within pregnancy. Funnel plots and a test for small study effects were not undertaken due to the small number of studies in each meta-analysis.[29,33]

3. Results

The searches identified 10367 records (before duplicate removal) (Figure 1), with 17 articles (reporting on 13 studies) being eligible for inclusion after screening and full paper review; six studies reported pregnancy outcomes[34–40] and nine studies reported child health outcomes.[41–49] Three studies were reported across two articles each: RESPIRE,[39,48] Nepal step-wedge ICS and LPG intervention[38,49] and ethanol cookstove[35,50] (Appendix 2).

3.1. Study characteristics

Of the six studies (seven articles) investigating a range of pregnancy outcomes (Table 2), all were RCTs and stove-based interventions (Figure 2) (e.g., ICS=3, ethanol stove=1 and LPG and ICS=2). Study quality was found to be strong (n=3), moderate (n=1) and weak (n=2) with studies being classified as weak where a lack of detail prevented a confident assessment of quality.

All of the nine (nine articles) child health outcome studies, comprising eight RCTs[41,43–49] and one interrupted time series,[42] investigated ICS interventions; with one study having both an ICS and an improved fuel (briquettes).[45] Study quality was found to be strong (n=6), moderate (n=2) and weak (n=1) respectively, with moderate or weak study quality designated due to the study design and outcome measurements.

Household air pollution measurements were reported in 10 studies, with a reduction in pollutant levels observed in four ICS interventions,[39,41,45,47,48] and two ICS/LPG interventions;[38,51] none of which were below the WHO-IAQ guidelines.

3.2. Pregnancy outcomes

3.2.1. ICS interventions vs traditional cooking

3.2.1.1. Birthweight

Four studies undertaken in India,[37] Nepal,[38] Ghana[40] and Guatemala,[39] compared ICS to traditional stove cooking, with variation in deployment date of the ICS ranging from before conception to final stage of pregnancy (Table 2). Timing of birthweight measurement varied between studies, recorded within 24 hours[40] (n=1), 48 hours[39] (n=1) and 72 hours[38] (n=1) of birth, or by maternal self-report.[37] The meta-analysis showed a higher absolute mean birthweight of 25.94 g (95% CI: -16.18 - 68.05) (figure 3) in ICS compared to traditional stove cooking, but the wide confidence interval for birthweight meant the association was insignificant . An exploratory sub-analysis restricted to those studies (n=3) in which the ICS was deployed within the third trimester of pregnancy only, gave a similar result (25.99 g; 95% CI: -24.01 - 78.99) (Appendix 3).

3.2.1.2. Low Birth Weight (LBW)

Three of the four studies which investigated birthweight also reported prevalence of LBW (Nepal,[38] Ghana[40] and Guatemala[39]), in addition to a study investigating only LBW in rural Bangladesh;[34] which deployed the ICS intervention within the first trimester and recorded birthweight within 72 hours of delivery. All studies except for one[34] (which provided no relevant definition), categorised LBW as a birthweight of <2500 g. Only one study (Bangladesh)[34] observed a decrease in the odds of LBW associated with an ICS intervention compared to traditional cooking (Table 3). In Nepal[38] there was no observed change in odds of LBW with the timing of intervention deployment by stage of pregnancy, after adjusting for confounders. In the meta-analysis, there was an observed decrease in the odds of LBW in the intervention compared to control groups (OR: 0.73; 95% CI: 0.61 - 0.87) (Figure 4). Two additional sub-analyses were undertaken (Appendix 4 and 5), showing similar results when the intervention was deployed in the first trimester (OR: 0.73; 95% CI: 0.54 - 0.97) in the intervention compared to the control group. However, when the ICS was deployed in the third trimester there was no evidence of an effect in the odds of LBW between the intervention and control arms (OR: 1.04; 95% CI: 0.73 - 1.47).

3.2.1.3. Preterm birth (PTB) and Small for Gestational Age (SGA)

Only two studies, in Nepal[38] and Ghana[40] investigated the effect of ICS on risk of preterm birth and SGA, with one[38] defining preterm birth as delivery before 37 weeks; in the other no definitions could be ascertained.[40] In the meta-analysis (figure 5 and 6) no clear evidence of a decrease in the odds of PTB or SGA with the intervention was observed (OR: 0.89; 95% CI: 0.67 - 1.17; OR: 1.02; 95% CI: 0.86 - 1.20, respectively).

3.2.2. Ethanol fuel interventions

A large trial was undertaken in Nigeria which investigated the effect of an ethanol cookstove intervention deployed at 18 weeks gestation compared to firewood, reporting multiple pregnancy outcomes[50] and blood pressure during pregnancy.[35] Some health improvements were identified (Table 3), including an increase in birthweight (Adjusted mean difference: 197 g; 95% CI: 25 - 368), and an increase in gestational age at delivery (Adjusted mean difference: 1.6 weeks; 95% CI: 0.04 – 3.2). No significant exposure-response relationships were observed. Additionally, no significant decrease in diastolic blood pressure during pregnancy was observed in the ethanol group compared to the firewood group. However, all controls were given information regarding the health harms of cooking smoke and details on how to reduce their exposure (e.g., cooking in a well ventilated room or cooking outside), reducing the ability to observe the true effect of the full intervention. In addition, the study was powered to detect an effect size difference between control and intervention groups for birthweight and preterm birth only, with many of the outcomes being underpowered, along with a low number of users in the firewood group.

3.2.3. LPG stove interventions

Two LPG stove interventions were investigated, one comparing LPG stoves deployed at 28 weeks gestation to traditional cooking in rural Ghana[40] and the second comparing LPG stoves to ICS both deployed prior to conception in rural Nepal.[38] Both studies showed no statistical significant improvement in pregnancy outcomes (birthweight, LBW, PTB, gestational age, SGA and stillbirth); however, in Nepal there was only a 50% compliance with the intervention measure. Blood pressure was also investigated in a subsample of the Ghana Randomized Air Pollution and Health Study (GRAPHs),[51] showing no statistically significant reduction in blood pressure in the intervention (combined LPG stoves or ICS) group compared to the traditional cooking group. However, a significant exposure-response relationship with CO was observed. Due to the differences in control group characteristics and variation in the timing of intervention deployment between these two studies a meta-analysis was not performed.

3.3. Child Health outcomes – Improved Cookstoves

3.3.1. Acute Respiratory Infection and Acute Lower Respiratory Infection

Of the nine studies reporting ARI and ALRI, in Ethiopia,[41] Guatemala,[42,48] Peru,[43] Rwanda,[44] Gambia,[45] Malawi,[46] Mexico,[47] and Nepal,[49] one used swabbing to detect pneumococcal nasopharyngeal carriage at a single time point as a proxy for ARI,[45] three used a non-specific definition[42,47,49] and five used the WHO Integrated Management of Childhood Illnesses (IMCI) definition of pneumonia and severe pneumonia.[41,43,44,46,48] ARI and ALRI were assessed by trained nurses (n=5), a fieldworker (n=1), maternal reports (n=1), nasopharyngeal swabs samples (n=1) and both maternal reports and fieldwork assessment (n=1). One study[46] also reported asthma and death as adverse events and another[49] reported a decrease in persistent cough and wheeze; however, there was no evidence for a reduction in fever, severe ALRI or ear discharge (actual result not reported). Only one study[48] observed a significant decrease in fieldworker assessed ARI risk (risk ratio 0.56; 95% CI:0.32-0.97) and a significant exposure-response relationship (RR: 0.82; 95% CI: 0.70-0.98). Three studies were excluded from the meta-analysis as the articles only reported effect estimates[47,49] or did not report a rate/count of the number of events;[45] in addition one study only reported ARI.[41] In the meta-analysis, ARI (figure 7) was observed to decrease in the intervention group (RR: 0.94; 95% CI: 0.88-1.01); however there was a substantial level of heterogeneity observed (I^2 59.4; $p<0.13$]). The level of heterogeneity was also high in the ALRI meta-analysis (figure 8) (I^2 80.4%; $p<0.01$]); with overall it being unclear whether there is a decrease in the rate of ALRI in the intervention compared to the control group (RR: 0.75; 95% CI: 0.55 - 1.03); with the confidence interval including both the null and a substantial benefit. In the stratification by geographic region, studies undertaken in Latin America, which were both located at high geographic elevation, displayed a decrease in the risk of ALRI in the intervention compared to control (RR: 0.70; 95% CI: 0.53-0.93). However, this effect was not seen in studies undertaken in Africa (RR: 1.01; 95% CI: 0.59 - 1.73), where a considerable level of heterogeneity remained (I^2 76%).

3.3.2. Burns

Cooking-related burns among children were reported as secondary or adverse health outcomes in three studies (Ethiopia,[41] Rwanda,[44] Malawi[46]); however, only one study[44] provided a definition of maternal-reported burns in their child occurring in the two months before the fieldworker visit. Of the three studies, only one study[44] showed clear statistical evidence of a decrease in the frequency of burns in the intervention group, at an individual study level. In the meta-analysis (figure 9) cooking using an ICS was observed to decrease the risk of burns (RR: 0.66; 95% CI: 0.45-0.96) compared to the control group.

3.4. Assessment of Intervention Compliance

Difference in the measurement and reporting of intervention compliance was observed between all included studies, looking at stove use,[37,41,43–45,48] functioning of stove[39,41,44,48] and sole use of new fuel[45] (Appendix 6). Of the 13 included studies four did not report compliance [34–36,42,47], one study obtained self-reported measures of compliance,[37] four studies used both self-report and fieldworker observations,[41,43–45] three studies used fieldwork observations[38–40,48,49,51] and a single study used objective stove-use monitors.[46] Only six out of the nine studies measured compliance, and those reported the level of compliance to range from 41 – 90% for use of the intervention stove, with one study[44] reporting reducing compliance across the trial period.

4. Discussion

This systematic review identified 13 eligible studies exploring the impact of HAP intervention measures (which presented seven pregnancy and nine child health outcomes), undertaken in a variety of LMIC settings, with a range of follow-up times and health outcomes. All interventions included were structural (e.g., improved cookstoves, chimneys) or clean fuel transitional interventions aimed at harm mitigation; often with complex designs (e.g., continuous intervention deployment) of multiple interventions and reported health outcomes. There was a range of study methodological quality with the weakest studies being hampered by poor reporting; in addition to differing outcome definitions, measurement timings in relation to health events, intervention deployment and assessment of compliance. In addition, this systematic review goes beyond that on the Thakur et al.[52] review including three large scale peer reviewed papers providing 1,271 observations for pregnancy outcomes and 25,195 child observations, a broader geographical scope, addition of grey literature and inclusion of childhood burns as a health outcome.

Within this systematic review, evidence synthesis suggests that the use of ICS results in a reduction in risk of LBW, burns and ALRI among children aged under five years in high altitude wood cooking settings in Latin America. However, these results could be due to differing situational factors of high altitudes compared to lower altitudes, for example lower temperatures and reduced ventilation[53] as well as differences in respiratory physiology.[54] Misclassification of health outcomes is also likely to have been further compounded by the timing of the intervention in relation to the disease progression, reducing the potential observed effect. In addition, exposure-response relationships indicates that $PM_{2.5}$ needs to be reduced to low levels to reduce ALRI risk;[55] as reflected by the WHO-IAQ. It is also recognised that any reduction in PM2.5 due to HAP exposure is of wider benefit for child health. Further randomised controlled trials to assess effectiveness for improving pregnancy outcomes should deploy the selected intervention prior to or early in the first trimester, as this reflects the period in which the foetus is most vulnerable to adverse impacts of air pollution exposure;[56–58] supported by our finding that deployment in the first trimester may reduce risk of LBW.[34,38] In addition, the greater mean birthweight observed with use of ICS compared to controls, could have clinical significance even though no statistical significance was observed; corroborated with substantive body of observational evidence documenting the health benefits of cleaner cooking. In addition, to improvements in pregnancy outcomes being seen within modest reduction in CO exposure.[59] Biological plausibility between HAPs and pregnancy or child respiratory outcomes has been well documented.[12] Carbon monoxide exposure and reduction in maternal lung function, results in oxidative stress, reducing oxygen availably to the foetus.[12] However, there is less understanding of the role of PM, but PM can reduce maternal lung function and cause inflammation.[60] Conversely, PM reaches deep inside the immature lungs of children causing inflammation, oxidative stress and reduces lung development.[61] HAPs do not directly cause burns but instead the stove safety is the mechanism for reducing harm. However, for the other included health outcomes it is difficult to draw any substantive conclusions as to the health benefit of the respective interventions due to variations in setting, contextual characteristics, outcome assessment. timing of intervention deployment, intervention follow up, study quality and sample size; which is consistent with previous evaluation of HAP interventions with regard to other outcomes.[7,16,62]

Duration of follow-up is an important additional consideration to timing of intervention deployment. The unresolved heterogeneity within the ALRI meta-analysis, which could not be explained by differences in study setting or design, was driven by the study undertaken by Mortimer *et al.* 2017;[46] who recruited children up until six months before the end of the study, resulting in an internal variation in follow-up duration. At the other end of the spectrum Litchfield 2018[45] assessed the outcome measure at a single time point only four months after the interventions were deployed using a proxy measure for ARI; meaning that this study could not be included within the meta-analysis as it was not a rate. Smith *et al.*, 2011[48] completed weekly visits over 14-18 months to determine the number of ARI episodes. Additionally, only six out of eight studies observed ARI outcomes in children after six months of age, as new stove use has been observed to reduce and stabilise after 200 days after intervention deployment,[63] therefore short follow up duration would be an overestimate of stove use and raises potential comparison issues between pre and post six month ARI estimates.

As well as simultaneous use of multiple domestic fuels and/or cooking apparatus – ‘stacking’, a change in stove use over time and the observed low levels of compliance may explain the heterogeneity observed in both health benefits and harms. Conclusions about the role of compliance in uptake and sole use of the intervention are limited, as self-reported measures do not capture if the stove is in good condition[64] and may be an overestimate, due to subject to observer or social acceptability bias.[65] Mortimer *et al.* 2017[46] attempted to use stove monitors for objective assessment with limited success. Stove monitoring would allow participants to be blinded for stove usage compliance observations but would not provide detail of fuel or stove stacking.[65] In addition, intervention stove use typically waned over time due to disrepair, with study investigators often providing resource for repairing and replacing stoves, thereby potentially reducing real-life applicability and generalisability. The Nigerian Ethanol cookstove intervention team provided health promotion advice on how to reduce pollution[35,50] to all which may be why there was a smaller difference between intervention and control groups; however it does present a more realistic real-world scenario. In addition, educational packages are often lacking for many interventions, but may provide a vital tool to encourage uptake and improve long-term compliance. A lack of compliance may also be the underlying reason as to why only two out of the eight studies with reported HAP measurements achieved levels below the WHO-IAQ levels, consistent with other findings;[17] however there were differences in air pollutant measurement type, location, duration between the studies and potential attenuation through neighbours not receiving the intervention.[15] In addition, those studies reporting a reduction in HAP between the intervention and control, did not alter the summary effect size for birthweight (n=2; Appendix 7), LBW (n=2; Appendix 8) and ARI (n=2; Appendix 9). Few studies investigated an exposure-response relationship, which limits any discussion on the presence of an exposure-response relationship in the absence of any treatment effect.

As all the identified eligible interventions were structural or clean fuel transitional interventions, albeit it within the limitations of the search strategy (e.g., synonyms of cleaner fuels), we identified a knowledge gap concerning the effectiveness of behavioural and community led interventions (e.g., outdoor cooking, using dry wood, ventilation) to reduce maternal and child health harms of HAP exposure. Short-term harm reduction, community-led, initiatives should not be neglected, as they have the potential to reduce exposure[66–68] and deliver a health benefit.[69] Future interventions need to take into consideration contextual, community and end-user needs,[7,16] including engagement with government, stakeholders and investors;[70] so that the community can continually invest in interventions to maintain sustained usage.[71] The RCT study design allows for a robust comparison of the benefits of the intervention enabling higher methodological quality assessment, investigation of the exposure-response relationship,[72] and evaluation of socioeconomic implications.[73] However, study periods are often relatively short and participants are encouraged/incentivised to use and engage with the interventions,[45] and so they typically fail to fully account for decreasing intervention uptake and usage over time, thereby limiting the achievement of a sustained HAP exposure reduction and health benefits.[44] Additionally, multi-disciplinary studies should address improved criteria/procedures for assessment of health outcomes, (as existing studies have been identified as adopting unclear and inconsistent health outcome definitions), alongside independent objective assessment (e.g., by healthcare workers) of health outcomes to aid blinding and reduce risk of observation bias. Our recommendations to improve the evaluation of HAP intervention measures, require appropriate research funding investment, resources and expertise to undertake such trials of complex intervention measures in low-income settings. Complex interventions may be difficult to standardise,[1] and improvements which could help reduce variation between trials should be encouraged whilst not unduly limiting innovation in intervention development.

The systematic review highlights the variation in study design, intervention type and outcome, which limits the number of comparable studies. Therefore, it was not possible to wholly address uptake and efficacy of HAP interventions; but only to identify and assess quantitative data reporting the relationship between intervention (e.g. ICS/fuel) uptake and maternal and child health outcomes. Despite the potential documented benefit of ICS, there is a move away from ICS to cleaner fuel to be able to achieve the WHO-IAQ and address the health impacts of HAPs, due to the exposure-response curves indicating a need for reduction to very low levels. The HAPIN trial,[74–76] an ongoing four country LPG stove RCT, with rigorous methods including free fuel to incentivise compliance, could provide important results to strengthen the evidence for new and existing child and maternal health outcomes. We recommend large scale trials reporting multiple health, HAP and uptake outcomes adhering to full reporting procedures including a summative assessment of all outcome measures in a published article, providing better reporting and dissemination of the benefits of such interventions. In addition, no study were found reporting exposure to HAP from heating and lighting. Households have little or no choice of alternative options and is likely to be a major source, therefore altering cooking practice where heating is required will have little effect on exposure. Conversely there are other good options of lighting intervention (e.g., solar lamps) which can be explored. This review highlights an existing research gap in short-term transitional harm reduction interventions, which are required to make air quality and health improvements in the short term. It could be argued that in countries with limited resources there should be a focus on the consolidation of existing evidence, which while relatively weak, can be useful for developing actionable evidence for policymakers[72] on the effectiveness as well as facilitators and barriers to implementation and adoption of HAP interventions.

5. Conclusion

This systematic review shows that ICS interventions have the potential to reduce ARI risk among those living in high altitude settings, incident burns in children under five years and risk of LBW. However, there are future research and policy implications for funding and development of effective community orientated short-medium and long-term household intervention measures, which should be adequately investigated using robust study methodology. These interventions may deliver a substantial benefit for child and maternal health, and would help support sustainable development in LMIC settings worldwide.

Author Contributions

KEW: Conceptualisation, methodology, data curation, formal analysis, visualisation, writing original draft. **EDC**: Conceptualisation, methodology, data curation, Writing - review & editing. **DJM**: Methodology, Writing - review & editing. **MJP**: Methodology, Writing – review & editing. **HLL and JS**: Data curation, Writing - review & editing. **SEB**: conceptualisation, supervision, reviewing and editing**, SMH and GNT**: Supervision, Writing - review & editing. **RD, FDP, SMG and DW**: Writing - review & editing

Conflict of interest statement

We declare no competing interests

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Artwork and Tables with Captions

Tables

Table 1: Study eligibility PICOS criteria

Populations	Pregnant women Children under five
Interventions	Household air pollution intervention
Comparators	Standard practice or alternative intervention
Outcomes	**Pregnancy outcomes:** IUGR, birthweight, preterm birth, pre-eclampsia, gestational diabetes, maternal mortality, perinatal/infant mortality, stillbirth and miscarriage **Child health outcomes:** upper and lower respiratory tract infections, pneumonia, asthma, respiratory distress syndrome, otitis media, impaired neurodevelopment, mortality and burns
Study designs	Randomised control Trials Non-randomised control trials Quasi-experimental or natural experiments

Table 2: Methodological, outcome and situational characteristics of included studies

Publication	Study type	Intervention and time of delivery	Control	Population	Eligibility criteria	Health outcomes and definitions	Follow up period	Household air pollution measurements	Compliance	Geographical characteristics	Study Quality ¶
Pregnancy Outcomes											
Ahmed *et al.*, (2015)[34] §	C-RCT N=1267	ICS – “$100 cookstove” n=628	Traditional cookstove (biomass fuels) n=639	Pregnant women	8-12 weeks gestation at time of enrolment	LBW – measured at home or a health care facility within 72 hours of delivery	8-12 weeks gestation until 42-day post-partum	None taken	Not reported	Shahjadpur sub-district, Bangladesh	Weak
Alexander *et al.* (2017)[35]	RCT N=324	Ethanol Clean Cookstove and information on the dangers of smoke exposure and how to reduce exposure. n= 162	Standard practice: firewood or kerosene and given information on the dangers of smoke exposure and how to reduce exposure. Data was extracted for the firewood only control group. n= 162	Pregnant women attending antennal clinics who cook on Kerosene or firewood	• Have a child between 2-8 months • Cooks in an enclosed cookhouse • Mother is not HIV positive or a smoker • Does not live with a smoker • Does not cook for a living • Has not previously has a high risk pregnancy	Blood pressure (SBP and DBP) taken at 20 weeks, 26 weeks, 30 weeks, 34 weeks, 38 weeks. An average of three reading recorded after being seated for 10 minutes and on the left arm.	18-38 weeks gestation	Reported in Alexander 2018	Not reported	9 selected village in Ibadan Nigeria, peri-urban setting	Strong
Alexander *et al.* (2018)[36]						Birthweight (g) Preterm (delivery before 37 weeks gestation) Stillborn (death after 24 weeks gestation) Miscarriage (Fetal loss before 24 weeks) Gestational age (weeks gestation at birth) Birth length (cm) Head Circumference (cm) Respiratory rate (breaths/min) Neonatal death Birth defects Perinatal mortality (Stillbirth or neonatal death)	18 weeks gestation to 6 weeks post pregnancy	72 hours personal $PM_{2.5}$ Rainy season – Intervention = n=114, Mean (SD) 61(74) µg/m^3 Control = n=116 Mean (SD) = 66(82) µg/m^3 Dry Season – Intervention = n=99, Mean (SD) = 118(166) µg/m^3 Control = n=98 Mean (SD) = 102 (102) µg/m^3	Not reported		
Hanna *et al.* (2016)[37]	RCT N= 2575	Three phases. Gram Vikas improved stove received by 1/3 is phase one and another 1/3 in phase two	Traditional cooking (firewood, crop residue, or cow dung). The last 1/3 received Gram Vikas improved stove at the end.	Participants residing in households within study area	Not stated	Birthweight, stillbirth or miscarriage and infant mortality. No definition provided, but were self-reported	Stove placement and follow up occurred between 2006-2010 (4 years)	Personal Exhaled CO (Micro Medical CO monitor) Intervention difference from baseline: -0.23ppm (SD:0.196) Control Mean: 7.128 ppm	Self-reported stove use. 60% of participants reported correct usage.	Orissa States, Rural India where 40% live below the poverty line	Weak
Katz *et al.* (2020)[38]	Step-wedge RCT Nepal Cookstove Intervention Project **Trial 1:** N= 3706 (2397 live	**Trial 1:** ICS Environfit International (Proportion of pregnancy exposure to ICS, <33, 33-65, 66-99, 100%)	**Trial 1**: Traditional biomass cooking (i.e. ICS was given after birth). **Trial 2**: LPG stove vs. ICS n= 270	Married women age 15-30	Household has one married women (15-30 years), a child under 36 months and does not already use LPG stove or electricity	Birthweight (g) taken within 72 hours of birth LBW (>2500g) Gestational Age (weeks) Preterm (before 37 weeks) SGA (sex and gestational-age-specific birthweights fell below the 10th percentile of	Women recruited before conception and followed up until birth. Birth included coloured over a 2-year period	Stove area measurements (Av. 21.7 hours) **Trial 1:** $PM_{2.5}$: TB = Mean: 1380 µg/m^3 (95% CI: 1336, 1425)	Weekly visit to encourage and check stove use. **Trial 1**: 90% reported use of alternative	Village development communities in rural southern low land Nepal, relying on subsistence farming	Strong

	births separated by gestation in pregnancy ICS was deployed) **Trial 2**: N= 1851	**Trial 2:** LPG stove n= 279				the inter-growth population distribution using the upper bounds of weekly published data	for trial 1 and 1-year period for trial 2.	ICS = Mean 936 μg/m^3 (95% CI: 895,978) CO: TB = Mean 11.0 ppm (95% CI: 10.6,11.4), ICS = Mean 6.7 ppm (95% CI: 6.4,7.1) **Trial 2:** PM$_{2.5}$: ICS = 885 μg/m^3 (95% CI: 810,959) LPG = 442 μg/m^3 (95% CI: 405,482) CO: ICS = Mean 5.5ppm (95% CI: 5.0,6.0) LPG = Mean 1.7 ppm (95% CI: 1.5,1.9)	stove at least once per week **Trial 2:** Alternative stove use was at 50%		
Thompson *et al.* (2011)[39]	RCT – RESPIRE N=266	Chimney stove n=134	Open wood fires (firewood) n=120	Pregnant women	Households with a pregnant women or a child < 4 months of age who cook on open wood fires	Birthweight measured within 48 hours of delivery. Low birthweight defined at <2500g	ICS was received by participants in the latter stages of pregnancy	48 hours personal CO. Open fire n=54 mean= 4.1 ppm (SD:3.2) (GM 3.2(SD:1.9)) Chimney n=49 mean 2.5ppm (SD:2.5) GM (1.8(2.1))	Weekly fieldworker home visits to check function and arrange if repair needed. Observations not reported	San Marcos, a rural and high altitude part of Guatemala.	Moderate
Wylie (2017)[40] ‡§	RCT – GRAPHs† Trial	Biolite improved cookstove (n=527) and LPG cookstove (n=361)	Three stone stove (firewood) n=526	Pregnant women at 28 weeks gestation	Primary cook at less than 28 weeks gestation, cooking on traditional fire, and are a non-smoker	Birthweight (g) measured within 24 hours of delivery. Preterm birth and SGA details obtained	Stove deployed at 28 weeks gestation and women followed to delivery	Reported in Quinn et al., 2017[51] 72 hours personal CO. Mean ICS: 1.43 ppm Mean Control: 0.63 ppm	Weekly stove use compliance by fieldworkers. Observations not reported	Rural Ghana	Strong
Under five child outcomes											
Adane et al., (2021)[41]	C-RCT N=5508 Pre-enrolment cross-sectional ARI prevalence is reported elsewhere [77]	Injera baking stove n=2750	Traditional biomass stove n=2758	Children under 4 years from biomass cooking low income households	Exclusive use of traditional biomass stove in an enclosed cooking area.	Trained nurse diagnoses ARI using the IMCI pneumonia algorithm. Burns were reported	Over 1 year from receiving intervention, taking measurements at three months intervals	Reported in Adane et al.,(2021)[78] One cookiFng hour area PM$_{2.5}$ Control: Mean 805 μg/m^3 (95% CI: 794–817). Intervention: Mean 465 μg/m^3 (95% CI: 458–472)	Self-report, direct field observation and unannounced visits. Observations not reported	A low-income rural community in Ethiopia	Strong
Harris *et al.* (2011)[42]	Interrupted time series N=4026	ONIL stove	Traditional cooking (firewood)	Whole population attending a basic health	-	Nurse diagnosed. Acute upper respiratory infection (AURI) = Non-productive cough, nasal congestion and	4 years, over which time the ICS was	None taken	Not reported	Quiche region of Guatemala	Weak

				care clinic in the village of Santa Avelina		sore throat, with or without low-grade fever ALRI = Non-productive cough, nasal congestion and sore throat, with fever>38°C	installed in 90% of homes				
Hartinger *et al.* (2016)[43]	C-RCT N=534	OPTIMA-improved stove n=267	Traditional stoves or open fires (solid fuels) n=267	Children under than age of 36 months residing in traditional biomass cooking households	Use of solid fuels, no public sewage connection and no intention to move during the study period	Symptoms observed by trained fieldworkers ARI = cough and/or difficulty breathing. ALRI = cough or difficulty breathing, with a raised respiratory rate (>50 per min in children aged 6–11 months and >40 per min in children aged >12 months) on two consecutive measurements.	Followed up for 12 months, counting weekly ARI events	Reported in Hartinger et al., (2013)[79] 48 hours personal and kitchen are PM$_{2.5}$ and CO. Kitchen PM - Control n=34 mean:189 μg/m^3 (95% CI:116-261) Kitchen PM Interventions n=30 mean: 148 μg/m^3 (95% CI:88-208) Personal PM Control n=40, Mean:129 μg/m^3 (95% CI: 82-176) Personal PM intervention n=37 Mean:104 μg/m^3 (95% CI:64-144) Kitchen CO control n=44 mean:5.8 ppm (95% CI: 33.3-8.2) Kitchen CO intervention n=39 mean: 4.7 ppm (95% CI:2.8-6.6) Personal CO control n=45 mean :1.4 ppm (95% CI:0.8-2) Personal CO intervention n=39 mean:1.5 ppm (95% CI:1-2)	Spot checking and monthly self-reported stove use. 90% of mother reported using the ICS.	High evaluation, rural small farming community in Peru	Strong
Kirby *et al.*, (2019)[44]	C-RCT N= 2174	ICS n=1073	Traditional biomass cooking (charcoal, wood, crop residue) n=1101	Children under the age of five	Agreed to receive intervention and a child under 4 years	Mother reporting child's symptoms to fieldworkers 7-day ARI: cough accompanied by rapid breathing or difficulty breathing. Current IMCI pneumonia: cough and difficulty breathing, accompanied by chest in drawing and/or rapid breathing ≥40 breaths/minute for children ≥12 months or	3 follow up visits at approximately 4 month intervals	Yes – 48 hours PM$_{2.5}$ measurement every three months n=148 Intervention: Mean: 224 μg/m^3 (median 154 μg/m^3, IQR 85–267 μg/m3) Control: Mean: 231 μg/m^3 (median 161 μg/m^3, IQR 91–285 μg/m^3)	Self-report and direct observation by trained field enumerators at each field visit. Declining use throughout study period, with 52.5% using intervention	Western rural Rwanda 9 96 administrative sectors containing 3,612 villages, with a total population of about 2.5 million persons)	Strong

						≥50 breaths/minute for children 2–12 months. Current Severe pneumonia (IMCI)‡ cough or difficulty breathing accompanied by severe symptoms (not able to drink, persistent vomiting, convulsions, lethargic/unconscious, stridor in a calm child, or severe malnutrition). Does not include children <2 months. Burns in previous two months			every day by the third visit, with stove use being over reported (ref – Thomas et al 2016)		
Litchfield (2018)[45]	RCT N=226	ICS and briquettes n=115	Traditional three stone stove (wood) n=136	Woman and children in wood cooking households	Cooking solely on biomass, in an enclosed cookhouse with a child between 2-8 months	Pneumococcal nasopharyngeal carriage was defined as a proxy for ARI	Followed up over 4 months after intervention	Yes – 48 hours $PM_{2.5}$ and CO stove located measurements $PM_{2.5}$ Intervention Mean = 659.8 μg/m^3 (SD:827.7), Control Mean = 573.1 μg/m^3 (SD:134.3) CO: Not reported	Self-report and fieldworkers checked compliance during weekly fuel drop offs. 41.4% continued to use 3-stone stove	Kombo East District, rural Gambia	Strong
Mortimer *et al.* (2017)[46]	C-RCT CAPS N= 10750	ICS (Philips HD4012LS biomass fan stove) n=5400	Traditional cooking on open fires n=5350	Children under the age of 4.5 years	Children under 4.5 years, continuous recruitment throughout the study as children become eligible, up until 6 months before the study end.	Assessed by trained healthcare staff. Non-severe IMCI pneumonia: cough or difficulty breathing and fast breathing (60, 50, or 40 breaths per min or higher in those aged <2 months, 2–12 months, and 1–5 years, respectively). Severe IMCI pneumonia: addition of chest in-drawing, stridor, or any general danger sign (inability to drink or breastfeed, vomiting, convulsions, lethargy, or unconsciousness). Death, burns and asthma was also recorded as adverse events	Followed up for every three months 2 years or until the end the trial which is ever is sooner	None taken	Self-report and stove use monitors were placed on one of the stoves in a randomly selected 10% sample of intervention households to record temperature fluctuations. Number of cooing event per day; Year 1: Mean:0.51 (SD:0.55) Year 2: Mean:0.34 (SD:0.40). After two year 50% reported using intervention	Sothern Shire river valley (Chikhwawa) and Northern (Karonga) Malawi	Strong
Schilmann *et al.* (2015)[47]	RCT N=668	Patsari stove n=338	Open wood fire or partial use of	Children under 4 years old residing in fuel	No specific inclusion criteria mentioned	Diagnoses by trained nurses. Lower respiratory infection - fast breathing, cough and	Every month for 10 months	Two subsamples (n=113) with a	Not reported	Six rural communities in the highland of	Moderate

			intervention n=330	wood households		difficulty breathing, Upper respiratory infection cough, congestion phlegm and sore throat		range 500-1000 $\mu g/m^3$. Intervention Median:200 $\mu g/m^3$ Control median: 300 $\mu g/m^3$ Reporting an 80% reduction		Michoacan, Mexico	
Smith *et al.* (2011)[48]	C-RCT RESPIRE N=534	Chimney stove n=269	Open wood fires n=265	Children under 4 months	Households with a pregnant women or a child <4 months of age that cooked on open wood fires	Physician diagnosed ARI, with chest radiography and RSV testing following standard practice. Trained fieldworker diagnosed ARI using WHO IMCI algorithm.	Weekly visits for 14-18 months	Personal 48 hours CO every 3 months. 50% reduction Intervention: 1.1 ppm Control: 2.2 ppm.	Weekly fieldworker home visits to check function and arrange if repair needed. Observations not reported.	San Marcos, a rural and high altitude part of Guatemala.	Strong
Tielsch *et al.* (2016)[49] §	Step-wedge RCT measuring before and after respiratory incidence Nepal Cookstove Intervention Project N=5254	ICS environfit international	Traditional biomass cooking	Household with a married woman (15-30 years) and a child under the age of 36 months	Household has one married women (15-30 years), a child under 36 months and does not already use LPG stove or electricity	ARI: Maternal report of 2 or more consecutive days of fast or difficult breathing accompanied by fever ALRI, cough, wheeze, burns also recorded	Weekly maternal reports over 6 months	HAP measurement taken but no results reported	Weekly visit to encourage and check stove use. Observations not reported.	Rural southern low land Nepal, village development communities based on subsidence farming	Moderate

N=Number study n=number randomised to each group, C-RCT = Cluster randomised control trial. GM=geometric mean. ICS = Improved cookstove ‡IMCI = Integrated Management of Childhood Illnesses.

† Quinn *et al.,* 2017[51] was a convenience sample from GRAPHs (N=44) reporting blood pressure 3-4 weeks after intervention was deployed.

‡ Asante *et al.*, 2019[80] stated no observed effect on pneumonia in children under five between the intervention and controls as part of the GRAPHS study. No results were reported, therefore not included.

§ These studies are conference abstract and authors were contacted to provide further details to no avail. Wylie *et al.* 2017[40] and Tielsch *et al.* 2016[49] are part of large RCT, supported by other published evidence. Ahmed *et al.* 2015[34] has not published the "$100 cookstove" trial, to the best of our knowledge, since the publication of the conference abstract in 2015.

¶ The breakdown of the study quality can be found in appendix 10.

Table 3: Included study health outcome results

Publication	Intervention	Control	Effect estimate
Pregnancy outcomes			
Ethanol cookstoves - Ethanol vs firewood			
Blood pressure (mm Hg) - Alexander *et al.* (2017)[35]	Normal blood pressure:39/48 Pre-hypertension:8/48 Hypertension:1/48	Normal blood pressure:42/53 Pre-hypertension:12/53 Hypertension: 1/53	Hypertensive verse non-hypertensive - Fisher's exact - *p*=0.10
Birthweight (g) - Alexander *et al.* (2018)[36]	Mean:3081 g, SD:470, n=50	Mean:2942, SD:403, n=48	AMD:197 (95% CI: 25–368) Adjusted for marital status and BMI
Gestational age (weeks) - Alexander *et al.* (2018)[36]	Mean:39.4, SD:1.6, n=51	Mean:37.9, SD:5.5, n=54	AMD:1.6 (95% CI: 0.04–3.2) Adjusted for marital status and BMI
Birth length (cm) - Alexander *et al.* (2018)[36]	Mean:46.6, SD:5.3, n=50	Mean:46.4, SD:5.4, n=47	Calculated† MD:0.2, SD:8 Reported *p*=0.92
Head Circumference (cm) - Alexander *et al.* (2018)[36]	Mean:33.8, SD:2.9, n=50	Mean:34.3, SD:2.1, n=48	Calculated† MD:-0.5, SD:4 Reported *p*=0.3
Respiratory rate (breath/min) - Alexander *et al.* (2018)[36]	Mean:125, SD:20.1, n=49	Mean:123, SD:10.7, n=46	Calculated† MD:2, SD:23 Reported *p*=0.53
Preterm birth - Alexander *et al.* (2018)[36]	5/51	5/54	Calculated† OR:1.07 (95% CI:0.29-3.9) Reported *p*=1.0
Stillborn - Alexander *et al.* (2018)[36]	0/51	2/54	OR could not be calculated Reported *p*=1.0
Miscarriage - Alexander *et al.* (2018)[36]	0/50	1/46	OR could not be calculated *p*=0.058
Birth defects - Alexander *et al.* (2018)[36]	0/50	0/50	OR could not be calculated Reported *p*=1.0
Neonatal death - Alexander *et al.* (2018)[36]	0/51	0/54	OR could not be calculated *p*=1.0
Perinatal mortality - Alexander *et al.* (2018)[36]	0/51	1/46	OR could not be calculated Reported *p*=0.058
Improved cookstove (ICS)			
Birthweight (g)			
Hanna *et al.* (2016)[37] ‡	Mean:2930, SD:985, n=241	Mean:2964, SD:886, n=400	Calculated† MD:-34, SD:77.4 Reported p=0.49
Katz *et al.* (2020)[38]	ICS <33% - Mean:2628, SD:443, n=133 ICS 33-65% - Mean:2647, SD:418, n=116 ICS 66-99% - Mean:2676, SD:408, n=104 ICS 100% - Mean:2657, SD:439, n=360	Mean: 2630, SD:443, n=558	AMD: -12.8 (95% CI: -107.1–81.4) AMD: -7.7 (95% CI: -112.7–97.4) AMD: 28.9 (95% CI: -87.2–145.0) AMD: -5.5 (95% CI: -122.6–111.6) Adjusted for secular trends and sex of infant
Thompson *et al.* (2011)[39]	Mean: 2797 (95% CI:2697, 2896), n=69	Mean: 2729 (95% CI:2654 to 2804) n=105	Beta coefficient 89g (95% CI: -27 to 204) *p*-value 0.13 Adjusted for height, gravidity, diastolic blood pressure and season of birth
Wylie (2017)[40]	Mean 2920, SD:460, n=488	Mean = 2890, SD:490, n=475	Calculated† MD: 30, SD: 30.6
Preterm birth			
Katz *et al.* (2020)[38]	ICS <33%: 39/165 ICS 33-65%: 19/141 ICS 66-99%: 27/125 ICS 100%: 105/474	212/943	ARR:1.38 (95% CI:0.97–1.97) ARR:0.81 (95% CI:0.50–1.32) ARR:1.41 (95% CI:0.91–2.20) ARR:1.66 (95% CI:1.08–2.57) Adjusted for secular trends and sex of infant

Wylie (2017)[40]	17/488	24/475	Calculated† OR:1.02 (95% CI:0.32–1.38)
Low birth weight			
Ahmed *et al.* (2015)[34]	110/469	179/499	Control (intervention as reference): AOR:1.76 (95% CI: 1.31–2.38) *p*<0.001 Adjusted for maternal age, maternal parity, BMI, gestational age, maternal education, SES score, time spend for cooking, husband smoking, SpCO 1st trimester
Katz *et al.* (2020)[38]	ICS <33%: 62/118 ICS 33-65%: 4/166 ICS 66-99%: 35/104 ICS 100%: 116/360	227/588	ARR:1.14 (95% CI:0.90, 1.44) ARR:0.83 (95% CI:0.59,1.17) ARR:0.92 (95% CI:0.63,1.34) ARR:0.95 (95% CI:0.65, 1.30) Adjusted for secular trends and sex of infant
Thompson *et al.* (2011)[39]	13/69	26/105	AOR: 0.74 (95% CI:0.33–1.66) Adjusted for maternal height, gravity, maternal diastolic blood pressure and season of birth
Wylie (2017)[40]	77/488	83/475	Calculated† OR:0.88 (95% CI:0.21–1.24)
Small for gestational age			
Katz *et al.* (2020)[38]	ICS <33%: 62/118 ICS 33-65%: 57/102 ICS 66-99%: 47/93 ICS 100%: 146/331	248/522	ARR:1.14 (95% CI:0.90–1.44) ARR:1.21 (95% CI:0.95–1.54) ARR:1.11 (95% CI:0.83–1.48) ARR:1.00 (95% CI:0.74–1.34) Adjusted for secular trends and sex of infant
Wylie (2017)[40]	103/488	99/475	Calculated† OR:1.02 (95% CI:0.32–1.38)
Other pregnancy outcomes			
Gestational age (weeks): Katz *et al.* (2020)[38]	ICS <33%: Mean:38.4, SD:3.1, n=165 ICS 33-65%: Mean:39.2, SD:2, n=141 ICS 66-99%: Mean:38.8, SD:2.7, n=125 ICS 100%: Mean:38.5, SD:2.7, n=474	Mean:38.6, SD:2.7, n=948	AMD -0.51 (95% CI: -1.03–0.001) AMD 0.27 (95% CI: -0.30–0.39) AMD -0.24 (95% CI: -0.75–0.39) AMD -0.75 (95% CI: -1.36 – -0.14) Adjusted for secular trends and sex of infant
Stillbirth/miscarriage: Hanna *et al.* (2016)[37] ‡	287/587	401/1060	Calculated† OR:1.55 (95% CI: 0.6–1.88)
Infant Mortality: Hanna *et al.* (2016)[37] ‡	28/488	42/701	Calculated† OR:0.96 (95% CI:0.45-1.6)
LPG stove			
Birthweight (g): Wylie (2017)[40]	Mean: 2870, SD: 490, n= 340	Mean:2890, SD: 490, n=475	Calculated† MD: -20, SD: 34.8 Reported *p*=0.68
LBW: Wylie (2017)[40]	59/340	83/475	Calculated† OR:0.99 (95% CI:0.69–1.42)
Preterm birth: Wylie (2017)[40]	17/340	24/475	Calculated† OR:0.99 (95% CI:0.52–1.87)
SGA: Wylie (2017)[40]	75/340	99/475	Calculated† OR:1.07 (95% CI:0.77–1.5)
Stillbirth: Wylie (2017)[40]	6/346	15/490	Unadjusted OR: 0.6 (95% CI: 0.2–1.5) (adjustment not reported)
ICS compared to LPG stove			
Katz *et al.* (2020)[38] Birthweight (g)	LPG: Mean:2742, SD:431, n= 207	ICS: Mean:2790, SD:427, n= 188	MD: -37 (95% CI: -122–47) (adjustment not reported)
Katz *et al.* (2020)[38] Gestational age (weeks)	LPG: Mean:39, SD:2.4, n=243	ICS: Mean:39.2, SD:2.2, n=248	MD: -0.3 (95% CI: -0.7–0.2) (adjustment not reported)
Katz *et al.* (2020)[38] Preterm birth	LPG: 47/243	ICS: 33/248	RR:1.45 (95% CI: 0.97–2.19) (adjustment not reported)
Katz *et al.* (2020)[38] LBW	LPG: 65/207	ICS: 44/188	RR:1.34 (95% CI: 0.97–1.86) (adjustment not reported)
Katz *et al.* (2020)[38] SGA	LPG: 86/184	ICS: 84/176	RR:0.98 (95% CI:0.79–1.21) (adjustment not reported)
Child health outcomes			

Improved cookstove (ICS)			
Acute Respiratory Infections			
Adane et al., (2021)[41]	Reported in child observations 1732/9860	Reported in child observations 1808/9932	AOR:0.95 (95% CI: 0.89–1.02) p=0.18 Adjusted for gender, age, baseline ARI, location of cooking, cookstove, frequency of baking event, visit
Harris *et al.* (2011)[42] Acute upper respiratory infection	2006: <1 year: 123 cases, Rate: 96.1 per 100 person-years assuming constant population (n=128), based on 2006 census 1–4 years: 214 cases, Rate: 37.8 per 100 person-years assuming constant population(n=566), based on 2006 census Calculated† combined ages (<1–4): 337 cases, Rate: 48.6 per 100 person-years (n=694)	2002: <1 year: 192 cases, Rate: 150 per 100 person-years assuming constant population (n=128), based on 2006 census 1–4 years: 248 cases, Rate: 43.8 per 100 person-years assuming constant population (n=566), based on 2006 census Calculated† combined ages (<1–4): 440 cases, Rate: 63.4 per 100 person-years (n=694)	Percentage decrease in rate: <1 year 35.9%, *p*<0.05 1-4 year: 13.7%, *p*<0.05 Calculated† percentage decrease <1-4:23.4%
Harris *et al.* (2011)[42] Acute Lower respiratory	2006: <1 year: 24 cases, Rate: 18.8 per 100 person-years assuming constant population (n=128), based on 2006 census 1-4 years: 82 cases, Rate: 14.5 per 100 person-years assuming constant population (n=566), based on 2006 census Calculated† combined ages (<1-4): 106 cases, Rate: 15.3 per 100 person-years (n=694)	2002: <1 year: 86 cases, Rate: 67.2 per 100 person-years assuming constant population (n=128), based on 2006 census 1-4 years: 151 cases, Rate: 26.7 per 100 person-years assuming constant population (n=566), based on 2006 census Calculated† combined ages (<1-4): 237 cases, Rate: 34.1 per 100 person-years (n=694)	Percentage decrease in rate: <1 year: 72.1%, p<0.05 1-4 years: 45.7%, *p*<0.05 Calculated† percentage decrease <1-4: 55.3%
Hartinger *et al.* (2016)[43] ARI and ALRI	Reported in person weeks ARI: 831/2976 ALRI: 25/554	Reported in person weeks ARI: 877/3012 ALRI: 40/563	ARI: Adjusted Risk ratio: 0.95 (95% CI:0.82–1.10) ARLI: Adjusted Risk ratio: 2.47 (95% CI:0.79–1.19) Adjusted for age
Kirby *et al.* (2019)[44]	Reported in child observations: 7-day ARI: 283/2850 Current pneumonia: 41/2574 Severe pneumonia: 26/2574	Reported in child observations: 7-day ARI: 441/3084 Current pneumonia: 55/2829 Severe pneumonia: 40/2829	7-day ARI APR: 0.75 (95% CI:0.60–0.93), *p*=0.009 Current Pneumonia: APR 0.87 (95% CI: 0.58–1.30) *p*=0.491 Severe Pneumonia: APR 0.75 (95% CI:0.45–1.24), *p*=0.256 Adjusted for age and gender
Litchfield (2018)[45] ARI - Pneumococcal Carriage	72/98	83/111	Calculated† OR:0.93 (95% CI:0.62-1.42)
Mortimer *et al.* (2017)[46] Pneumonia and severe Pneumonia	Reported in child-years: Pneumonia: 1255/7964 IR:15.76 (95% CI:14.89–16.63) per 100 child-years Severe Pneumonia: 186/7964 IR: 2.33 (95% CI:2.00–2.97)	Reported in child-years: Pneumonia: 1251/8027 IR: 15.58 (95% CI:14.72–16.45) per 100 child-years Severe Pneumonia: 145/8027 IR: 1.80 (95% CI:1.51–2.09)	Pneumonia: IRR:1.01 (95% CI:0.91–1.13) *p*=0.80. After adjustment for baseline values Severe Pneumonia: IRR:1.30 (95% CI:0.99–1.71) *p*=0.06
Schilmann *et al.* (2015)[47] Upper and lower ARI	ICS (not reported)	Firewood (not reported)	Upper ARI: AOR:0.840 (95% CI:0.689–1.025), IRR:0.789 (95% CI:0.701–0.888) Lower ARI: AOR:0.612 (95% CI:0.207–1.805), IRR:0.411 (95% CI:0.212–0.796) Adjusted for age, sex, vaccination, breastfeeding, nutritional status and household characteristics
	Combined ICS and firewood use (not reported)	Firewood (not reported)	Upper ARI: AOR:0.943 (95% CI:0.786–1.176), IRR:0.900 (95% CI:0.788–1.028) Lower ARI: AOR:0.873(95% CI:0.258–2.992), IRR:0.682 (95% CI:0.349–1.333) Adjusted for age, sex, vaccination, breastfeeding, nutritional status and household characteristics
Smith *et al.* (2011)[48] ARI	Reported in child weeks: ARI Fieldworker diagnosed - all: 321/14379 ARI Fieldworker diagnosed - severe: 26/14719 Clinical ARI - all: 124/15529 Clinical ARI - severe: 60/15553 Physician-diagnosed radiological pneumonia - all: 41/15558	Reported in child weeks: ARI Fieldworker diagnosed - all: 340/13939 ARI Fieldworker diagnosed - severe: 45/14310 Clinical ARI - all: 139/14871 Clinical ARI - severe: 76/14891 Physician-diagnosed radiological pneumonia - all: 44/14886	ARI Fieldworker diagnosed - all: Rate ratio: 0.91 (95% CI:0.74–1.13) *p* = 0.393 ARI Fieldworker diagnosed - severe: Rate ratio:0.56 (95% CI:0.32–0.97) *p* = 0.036 Clinical ARI - all: Rate ratio:0.78 (95% CI:0.59–1.06)

	Physician-diagnosed radiological pneumonia - severe: 25/15559 Physician-diagnosed RSV negative - all: 73/15542 Physician-diagnosed RSV negative - severe: 27/15564 Physician-diagnosed RSV positive - all: 43/15556 Physician-diagnosed RSV positive - severe: 30/15568	Physician-diagnosed radiological pneumonia - severe: 28/14891 Physician-diagnosed RSV negative - all: 77/14877 Physician-diagnosed RSV negative - severe: 42/14899 Physician-diagnosed RSV positive - all: 43/14879 Physician-diagnosed RSV positive - severe: 27/14897	Clinical ARI - severe: Rate Ratio: 0.67 (95% CI:0.45–0.98) Physician-diagnosed radiological pneumonia - all: Rate Ratio:0.74 (95% CI:0.42–1.15) *p*=0.231 Physician-diagnosed radiological pneumonia - severe: Rate ratio = 0.68 (95% CI:0.36–1.33) *p*=0.234 Physician-diagnosed RSV negative - all: Rate Ratio:0.79 (95% CI:0.53–1.07) *p*=0.192 Physician-diagnosed RSV negative - severe: Rate ratio:0.54 (95% CI:0.31–0.91) *p*=0.026 Physician-diagnosed RSV positive - all: Rate Ratio:0.76 (95% CI:0.42–1.16) *p*=0.275
Tielsch *et al.* (2016)[49] ARI	Not reported	Not reported	AOR: 0.87 (95% CI:0.67–1.13)
Burns			
Adane *et al.* (2021)[41]	Reported in child observations: 41/9860	Reported in child observations 51/9932	IRR:0.80 (95% CI: 0.54–1.22
Mortimer *et al.* (2017)[46]	Reported in child-years: 9/7964 IR: 0.11 (95% CI: 0.04–0.19)	Reported in child-years: 10/8027 IR:0.12 (95% CI:0.05–0.20)	IRR:0.91 (95% CI:0.37–2.23) p=0.83
Tielsch *et al.* (2016)[49]	Not reported	Not reported	AOR:0.68 (95% CI:0.48–0.95)
Kirby *et al.* (2019)[44]	Reported in child observation: 51/2850	Reported in child observations: 112/3090	APR:0.51 (95% CI:0.36–0.74) Adjusted for age and gender
Other child health outcomes			
Mortimer *et al.* (2017)[46] Asthma	Reported in child-years: 6/7964 IR: 0.08 (95% CI:0.02-0.14)	Reported in child-years: 10/8027 IR:0.02 (95% CI:0.01-0.06)	IRR:3.03 (95% CI:0.51–18.11) *p*=0.22
Mortimer *et al.* (2017)[46] Death	Reported in child-years: 3/7964 IR:0.04 (95% CI:0.00–0.08)	Reported in child-years: 4/8027 IR:0.05 (95% CI:0.00–0.10)	IRR:0.76 (95% CI:0.17–3.37) *p*=0.71
Tielsch *et al.* (2016)[49] Persistent Cough	Not reported	Not reported	AOR: 0.91 (95% CI:0.85–0.97),
Tielsch *et al.* (2016)[49] Wheeze	Not reported	Not reported	AOR:0.87 (95% CI:0.78–0.97)

Abbreviation are: OR=Odds Ratio, ARO=Adjusted Odds Ratio, p=p value, RR=Relative Risk, IR=Incident Rate, IRR=Incident Rate Ratio, APR=Prevalence Ratio, MD=Mean Difference, AMD=Adjusted Mean Difference, TB = Traditional Biomass

† Odds ratio calculated from data provided ‡ Results obtained from raw data provided in supplementary material

Figures

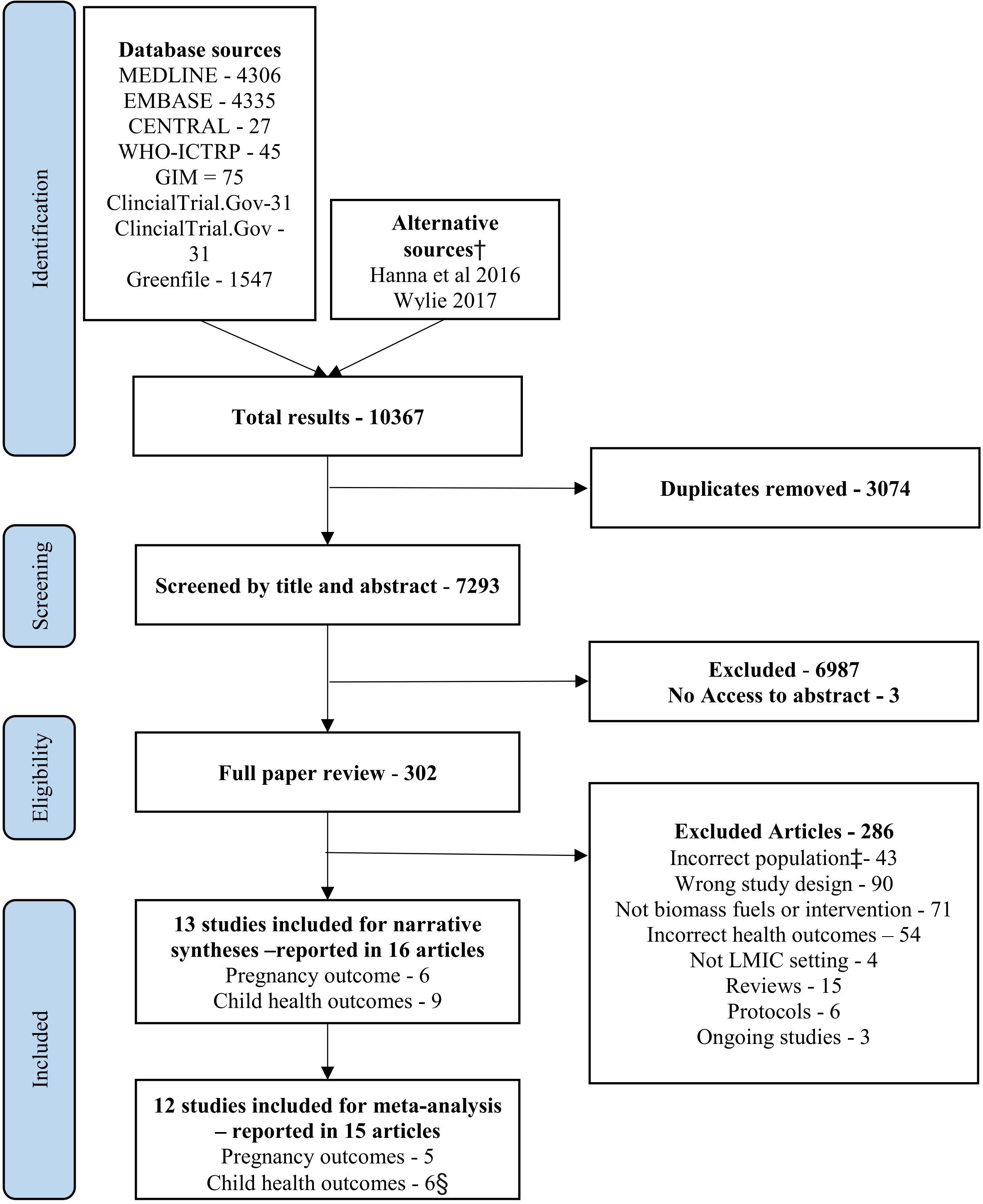

Figure 1: PRISMA flow diagram of search result and study selection. † Two studies were identified from alternative sources. Hanna *et al.,* 2016[37] was identified from a previous systematic review Thakur *et al.,* 2018[16] and Wylie *et al.,* 2017[40] investigation into available publish literature from the identification of the GRAPHs study through the ClinicalTrials.gov search. ‡Incorrect population are those studies that did not meet the population inclusion criteria, which included those studies where children above the age of five were also investigated by data from children under five could not be extracted separately. § Two child health outcome studies could not be included in the meta-analysis due to lack of data provided. Adane *et al.* (2020) was identified as pre-print by the search, with subsequent publication[41] during manuscript preparation.

Figure 2: Article characteristics by geographical region, with interventions type for pregnancy outcomes and duration of follow-up from intervention deployed to health outcomes measurement for child health outcomes.

Figure 3: Forest plot for the differences in birthweight (grams) between ICS and traditional cooking. Number of observations = 3049. A random effects model was used. Abbreviations: g=grams, MD = Mean Difference, 95% CI = 95% Confidence interval, I^2 = percentage variability of the effect estimates as a result of heterogeneity rather than chance, τ^2 tau-squared, Test of $\theta_i=\theta_j$: Q(3) = chi-squared with degrees of freedom, p = p value, Test of $\theta = 0$: z = z statistic for overall estimate.

Figure 4: Forest plot for the change in LBW between ICS and traditional cooking. Number of observations = 3456. A random effects model was used. Abbreviations: OR = Odds ratio, 95% CI = 95% Confidence interval, I^2 = percentage variability of the effect estimates as a result of heterogeneity rather than chance, τ^2 tau-squared, Test of $\theta_i=\theta_j$: Q(3) = chi-squared with degrees of freedom, p = p value, Test of $\theta = 0$: z = z statistic for overall estimate.

Figure 5: Forest plot for the change in SGA between ICS and traditional cooking. Number of observations = 2129. A random effects model was used. Abbreviations: OR = Odds ratio, 95% CI = 95% Confidence interval, I^2 = percentage variability of the effect estimates as a result of heterogeneity rather than chance, τ^2 tau-squared, Test of $\theta_i=\theta_j$: Q(2) = chi-squared with degrees of freedom, p = p value, Test of $\theta = 0$: z = z statistic for overall estimate.

Figure 6: Forest plot for the change in PTB between ICS and traditional cooking. Number of observations = 2811. A random effects model was used. Abbreviations: OR = Odds ratio, 95% CI = 95% Confidence interval, I^2 = percentage variability of the effect estimates as a result of heterogeneity rather than chance, τ^2 tau-squared, Test of $\theta_i=\theta_j$: Q(2) = chi-squared with degrees of freedom, p = p value, Test of $\theta = 0$: z = z statistic for overall estimate.

Figure 7: Forest plot of studies reporting rates of ARI, with definitions that are compared to the WHO IMCI criteria, between ICS and traditional cooking. Number of observations = 78962. A random effects model was used. Abbreviations: RR = Rate Ratio, 95% CI = 95% Confidence interval, I^2 = percentage variability of the effect estimates as a result of heterogeneity rather than chance, τ^2 tau-squared, Test of $\theta_i=\theta_j$: Q(5) = chi-squared with degrees of freedom, p = p value, Test of $\theta = 0$: z = z statistic for overall estimate, RCT = Randomised control trial.

Figure 8: Forest plot of studies reporting rates of ALRI, with definitions that are compared to the WHO IMCI criteria, between ICS and traditional cooking. Number of observations = 54343. A random effects model was used. Abbreviations: RR = Rate Ratio, 95% CI = 95% Confidence interval, I^2 = percentage variability of the effect estimates as a result of heterogeneity rather than chance, τ^2 tau-squared, Test of $\theta_i=\theta_j$: Q(4) = chi-squared with degrees of freedom, p = p value, Test of $\theta = 0$: z = z statistic for overall estimate, RCT = Randomised control trial.

Figure 9: Forest plot of studies reporting burns between ICS and traditional cooking. Number of observations = 41723. A random effects model was used. Abbreviations: RR = Rate Ratio, 95% CI = 95% Confidence interval, I^2 = percentage variability of the effect estimates as a result of heterogeneity rather than chance, τ^2 tau-squared, Test of $\theta_i=\theta_j$: Q(2) = chi-squared

with degrees of freedom, p = p value, Test of θ = 0: z = z statistic for overall estimate, RCT = Randomised control Trial.

Appendices

Appendix 1: MEDLINE search strategy (n=4306)

Appendix 2: Breakdown of the number of articles per study by intervention and health outcome.

Appendix 3: Sub-analysis of birthweight when ICS was deployed in the last trimester. Number of observations = 1828. Abbreviations: MD = mean difference, g= grams, 95% CI = 95% Confidence interval, I^2 = percentage variability of the effect estimates as a result of heterogeneity rather than chance, τ^2 tau-squared, Test of $\theta_i=\theta_j$: Q(2) = chi-squared with degrees of freedom, p = p value, Test of $\theta = 0$: z = z statistic for overall estimate.

Appendix 4: Sub-analysis of LBW when ICS was deployed in the first trimester. Number of observations = 1660. Abbreviations: OR = Odds ratio, 95% CI = 95% Confidence interval, I^2 = percentage variability of the effect estimates as a result of heterogeneity rather than chance, τ^2 tau-squared, Test of $\theta_i=\theta_j$: Q(1) = chi-squared with degrees of freedom, p = p value, Test of $\theta = 0$: z = z statistic for overall estimate.

Appendix 5: Sub-analysis of LBW when ICS was deployed in the third trimester. Number of observations = 1843. Abbreviations: OR = Odds ratio, 95% CI = 95% Confidence interval, I^2 = percentage variability of the effect estimates as a result of heterogeneity rather than chance, τ^2 tau-squared, Test of $\theta_i=\theta_j$: Q(2) = chi-squared with degrees of freedom, p = p value, Test of $\theta = 0$: z = z statistic for overall estimate.

Appendix 6: Type of intervention compliance observed, how it was measured and reported result by intervention type.

Appendix 7: Sub-analysis of birthweight when a reduction in HAP was observed with the intervention (ICS). Number of observations = 835. Abbreviations: MD = mean difference, g= grams, 95% CI = 95% Confidence interval, I^2 = percentage variability of the effect estimates as a result of heterogeneity rather than chance, τ^2 tau-squared, Test of $\theta_i=\theta_j$: Q(1) = chi-squared with degrees of freedom, p = p value, Test of $\theta = 0$: z = z statistic for overall estimate.

Appendix 8: Sub-analysis of LBW when a reduction in HAP was observed with the intervention (ICS). Number of observations = 1525. Abbreviations: OR = Odds ratio, 95% CI = 95% Confidence interval, I^2 = percentage variability of the effect estimates as a result of heterogeneity rather than chance, τ^2 tau-squared, Test of $\theta_i=\theta_j$: Q(1) = chi-squared with degrees of freedom, p = p value, Test of $\theta = 0$: z = z statistic for overall estimate.

Appendix 9: Sub-analysis of ARI when a reduction in HAP was observed with the intervention (ICS). Number of observations = 50192. Abbreviations: RR = Rate Ratio, 95% CI = 95% Confidence interval, I^2 = percentage variability of the effect estimates as a result of heterogeneity rather than chance, τ^2 tau-squared, Test of $\theta_i=\theta_j$: Q(1) = chi-squared with degrees of freedom, p = p value, Test of $\theta = 0$: z = z statistic for overall estimate.

Appendix 10: Breakdown of the results for the six components of the quality and risk of bias assessment.

Article	**Rating for Selection bias**	**Rating for study design**	**Rating for confounders**	**Rating for blinding**	**Rating for Data collection Methods**	**Rating for withdrawals and dropouts**	**Global rating**
Adane *et al.*, 2021	MODERATE	STRONG	MODERATE	MODERATE	MODERATE	STRONG	STRONG
Alexander *et al.*, 2017	MODERATE	STRONG	STRONG	MODERATE	MODERATE	STRONG	STRONG
Alexander *et al.*, 2018	MODERATE	STRONG	STRONG	MODERATE	MODERATE	MODERATE	MODERATE
Amhed *et al.*, 2015	MODERATE	MODERATE	Moderate	WEAK	WEAK	STRONG	WEAK
Hanna *et al.*, 2017	MODERATE	STRONG	WEAK	MODERATE	WEAK	WEAK	WEAK
Harris *et al.*, 2011	WEAK	WEAK	WEAK	MODERATE	MODERATE	MODERATE	WEAK
Hartinger *et al.*, 2016	MODERATE	STRONG	STRONG	MODERATE	MODERATE	STRONG	STRONG
Katz *et al.*, 2020	MODERATE	STRONG	MODERATE	MODERATE	STRONG	STRONG	STRONG
Kirby *et al.*, 2019	MODERATE	STRONG	MODERATE	MODERATE	STRONG	STRONG	STRONG
Litchfeild 2018	STRONG	STRONG	MODERATE	MODERATE	MODERATE	STRONG	STRONG
Mortimer *et al.*, 2017	MODERATE	STRONG	STRONG	STRONG	MODERATE	STRONG	STRONG
Schilmaan *et al.*, 2015	MODERATE	STRONG	MODERATE	WEAK	STRONG	MODERATE	MODERATE
Smith *et al.*, 2011	STRONG	STRONG	MODERATE	STRONG	STRONG	STRONG	STRONG
Teilsch *et al.*, 2016	MODERATE	STRONG	WEAK	MODERATE	STRONG	MODERATE	MODERATE
Thompson *et al.*, 2011	MODERATE	STRONG	MODERATE	MODERATE	MODERATE	WEAK	MODERATE
Wylie 2017	MODERATE	STRONG	MODERATE	MODERATE	MODERATE	MODERATE	STRONG